A SEMI-AUTOMATIC SYSTEM FOR THE ULTRASONIC MEASUREMENT OF TEXTURE

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INTRODUCTION

The texture (preferred grain orientation) of rolled metal plates influences a number of important mechanical properties such as their ability to be plastically formed into complex shapes. X-ray diffraction techniques can characterize texture in great detail but are unsuitable for real time process control. Furthermore, x-rays only sample the properties of a near surface layer, whereas the average properties throughout the thickness may be of greater interest. This paper describes an alternate texture characterization approach based on ultrasonic measurements of the anisotropy of plate wave velocities. Relationships have recently been established between the macroscopic elastic constants of a rolled metal plate and the coefficients of an expansion of the crystallite orientation distribution function (CODF) in terms of generalized Legendre functions [1]. It has also been shown that these coefficients can be determined from velocity measurements of ultrasonic plate modes [2,3]. Here a system is described which implements these ideas in a semi-automated fashion as would be required for process control applications. The measurement system consists of two sets of EMAT transducers and associated electronics, one for SH_o mode measurements and the other for S_o mode measurements. Each set consists of one transmitter and two receivers, separated by a fixed distance and placed at a variable angle with respect to the rolling direction of the plate. The pair of received signals are digitized and processed to determine the coefficients W_{400}, W_{420} and W_{440}, which can, in turn, be used to make first order predictions of pole figures. These steps are reviewed in detail and future directions are discussed.

THEORY

The rolled metal plate is modeled as a continuum, having macroscopic orthotropic symmetry (three mutually perpendicular mirror planes). The degree of preferred orientation of its crystallites are quantified by a crystallite orientation distribution function (CODF) represented by $w(\xi,\psi,\phi)$, where the arguments are Euler angles describing the orientation of crystallites with respect to the sample axes [1]. It is often convenient to expand the CODF as a series of generalized Legendre functions, $Z_{\ell mn}$, as defined by [4]

$$w(\xi,\psi,\phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} \sum_{n=-\ell}^{\ell} W_{\ell mn} Z_{\ell mn}(\xi) e^{-im\psi} e^{-in\phi}. \quad (1)$$

For cubic crystallites, symmetry dictates that the lowest order independent coefficients are $W_{000} = 1/2\sqrt{2}\,\pi^2$ (a normalization constant), and W_{400}, W_{420}, and W_{440}. Following the Voigt procedure for averaging elastic constants, the polycrystalline elastic constants, C'_{IJ}, of the orthorhombic plate may be expressed in terms of these four $W_{\ell mn}$ coefficients and the single crystal elastic constants, C^o_{IJ} [1]. Typical results are

$$C'_{44} = C^o_{44} + C^o\,[\,1/5 - 16/35\,\sqrt{2}\,\pi^2(W_{400} - \sqrt{(5/2)}\,W_{420})] \quad (2)$$

$$C'_{55} = C^o_{55} + C^o\,[\,1/5 - 16/35\,\sqrt{2}\,\pi^2(W_{400} + \sqrt{(5/2)}\,W_{420})] \quad (3)$$

$$C'_{66} = C^o_{66} + C^o\,[\,1/5 + 4/35\,\sqrt{2}\,\pi^2(W_{400} - \sqrt{70}\,W_{440})], \quad (4)$$

with similar relationships available for the remaining six independent elastic constants.

These elastic constants, and hence the $W_{\ell mn}$, can be inferred from measurements of ultrasonic wavespeeds. For thin plates, Lee, Smith, and Thompson [3] have shown that

$$\rho\{SH_o^{\,2}(45°) - \frac{1}{2}[SH_o^{\,2}(0°) + SH_o^{\,2}(90°)]\} = \frac{16C^o\pi^2\sqrt{35}}{35} W_{440} \quad (5)$$

$$\frac{\rho\{S_o^{\,2}(0°) + S_o^{\,2}(90°)}{2} - S_o^{\,2}(45°)\} = \frac{16C^o\pi^2\sqrt{35}}{35} W_{440} \quad (6)$$

$$\rho\{S_o^{\,2}(0°) - S_o^{\,2}(90°)\} = -\frac{32\sqrt{5}\pi^2 C}{35}\,(1 + \frac{2C_{12}^0}{C_{11}^0})\,W_{420} \quad (7)$$

$$\frac{\rho}{2}\{SH_o^2(45°) + \frac{1}{2}[SH^2(0) + SH_o^{\,2}(90)]\} = C_{44}{}^o + C^o\{1/5 + \frac{4\sqrt{2}\,\pi^2}{35} W_{400}\} \quad (8)$$

where $C^o = C^o_{11} - C^o_{12} - 2C^o_{44}$.

Here $SH_o(\theta)$ represents the velocity of the fundamental, horizontally polarized shear mode and $S_o(\theta)$ represents that of the fundamental symmetric Lamb mode, sometimes referred to as the extensional mode.

VELOCITY MEASUREMENT APPROACH

Equations (5)-(8) show that, in order to determine the coefficients W_{400}, W_{420}, and W_{440}, it is necessary to measure the velocity of two ultrasonic plate modes, the S_o and the SH_o at three propagation directions (0°, 45°, and 90° with respect to the rolling direction). For each mode, this is accomplished with a three probe system, as shown in the system block diagram in Fig. 1. One transducer is used as a transmitter

HARDWARE SYSTEM

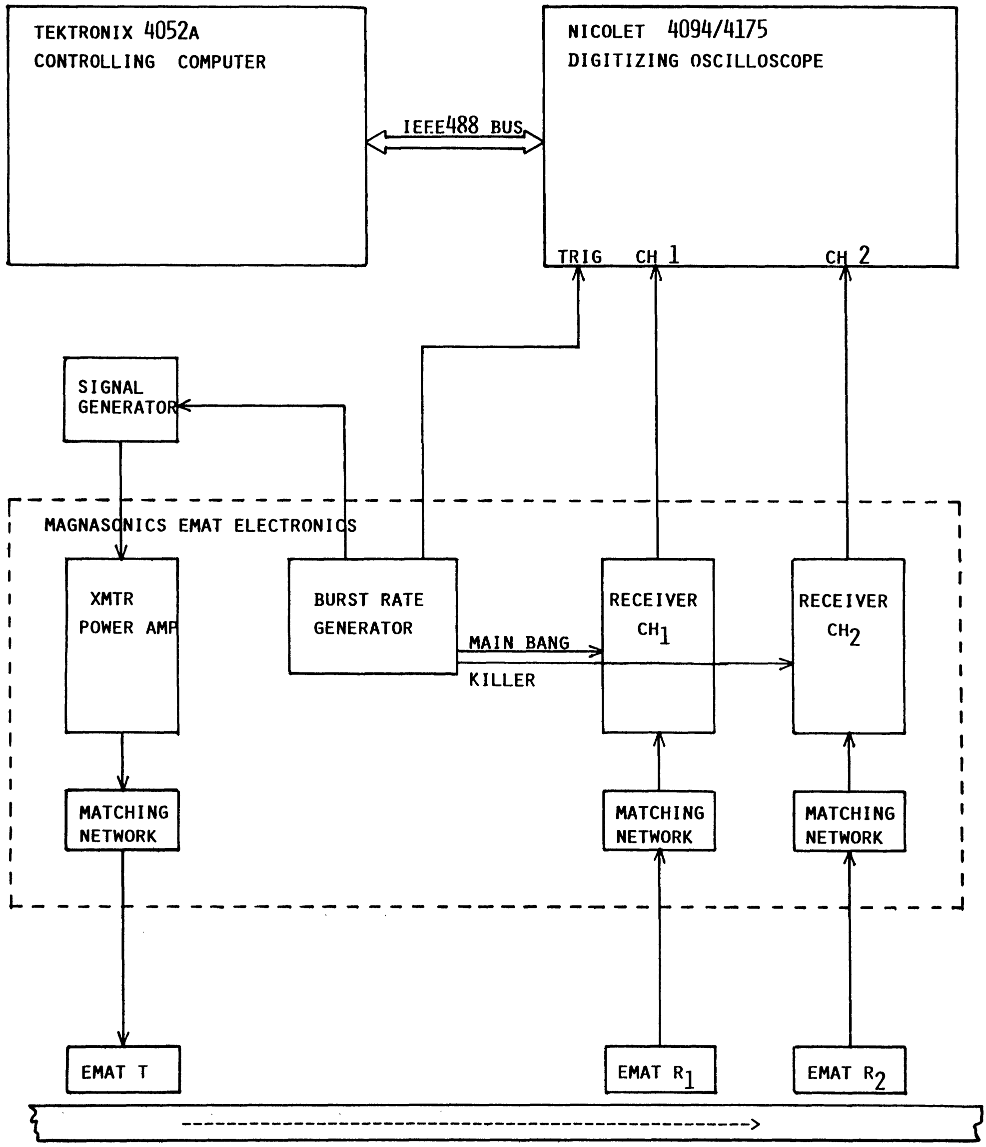

Fig. 1. Block diagram of the hardware used to measure velocity as a function of orientation with respect to the rolling direction in a plate.

and two act as receivers so that absolute velocities can be obtained. EMAT probes were selected because of their couplant free operation and ability to operate in high temperature environments as would be desired in process control applications. The ultrasonic velocity is determined by measuring the time difference between the two received RF bursts by digital cross-correlation techniques. Because many points on the waveform contribute to the answer, a precise time difference measurement is obtained.

Figure 2 shows the hardware system currently implemented. The Magnasonics EMAT Electronics (bottom) and associated signal generator (top) provide the driving, matching, and receiving functions for the EMAT probes. The Nicolet Digitizing Scope (middle) can digitize 8K points per channel with a spacing as small as 2ns per sample point, capturing a complete burst of RF in each channel. A Tektronix 4052A computer (not shown) controls data acquisition and signal processing. Due to memory restrictions, only 512 data points are used per channel with a sample spacing of 5ns per sample point. Use of a more modern computer in the near future will reduce this restriction.

MEASUREMENT PROCEDURE

Given the plate being inspected, the rolling direction is determined from physical inspection. Were this not possible, it could be determined from the ultrasonic data. The velocities of the S_o and the SH_o modes are then determined at the three propagation directions using the cross-correlation procedures. The difference in time is obtained to an accuracy of one sample interval; in this case 5ns. Effective distances between the receiver EMAT probes are known from initial calibrations experiments.

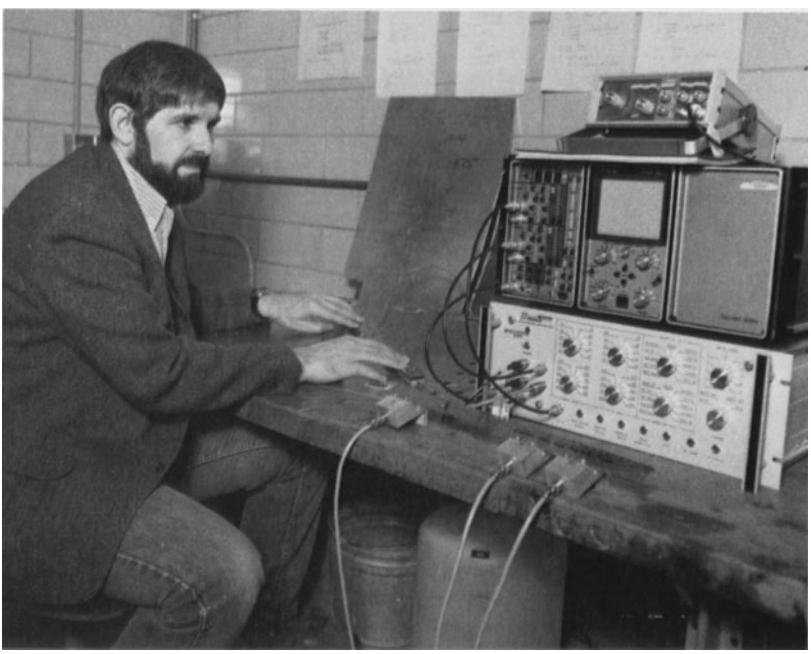

Fig. 2. A semi-automatic system for the ultrasonic measure of texture. Not shown is the computer used for data processing and calculation of CODF.

Therefore, velocity can be calculated directly from the time differential. The CODF coefficients W_{400}, W_{420}, and W_{400} are then calculated using Eqs. (5)-(8).

MEASUREMENT RESULTS

The system has been evaluated on a set of samples which have been independently characterized by a manually operated ultrasonic system based on the same principles [3-5] but using a time-average interval counter for the velocity determination. The repeatability of the velocity measurement was first examined. For the SH mode, measurements with 512 samples per waveform at 5ns intervals and with signal averaging of 16 repetitions showed a repeatability of ±5ns as would be expected. Based on a receiver separation of 10cm, this corresponds to a velocity measurement precision of approximately 0.02%.

Table I compares the values obtained with the digital system for the coefficient W_{440} to those obtained manually [5,6]. Also shown are values obtained on a few samples by neutron diffraction [7]. With the exception of one anomalous point, the agreement between the two ultrasonic systems is within 15%, with better performance obtained for most cases. When available, the neutron data is also in good agreement. The error of 15% is considerably greater than can be explained on the basis of the measurement precision and further work is required to define all contributing factors. Nevertheless, these initial results are quite encouraging.

Table I. Comparison of CODF W_{440} measurements.

Material	Manual W_{440}	Auto W_{440}	% DIFF	Neutron W_{440}
6061-T6 AL #1	-2.79E-4	-2.58E-4	-7.5	----
6061-T6AL #2	9.96E-4	8.98E-4	-9.8	----
6061-T6 AL #3	9.96E-4	7.03E-4	-27.0	----
ALCOA AL 629°	5.02E-3	4.75E-3	-5.4	4.9E-3
ALCOA AL 640°	3.50E-3	3.28E-3	-6.3	----
ALCOA AL 675°	3.03E-3	2.92E-3	-3.6	3.3E-3
304 Stainless #1	-2.80E-4	-3.13E-4	11.6	----
304 Stainless #2	2.71E-4	3.10E-4	14.3	----

The results for W_{400} and W_{420} are not yet as satisfactory. For W_{420}, the required S_o mode signals have very poor signal-to-noise ratios, which have recently been shown to be a result of improper tuning. It is anticipated the good results will be obtained when the tuning is corrected, as has been demonstrated for manual systems [5,6].

For W_{400}, the absolute measurement procedure appears to be a problem. Whereas Eqs. (5)-(7) only require relative measurements, Eq. (8) demands an absolute comparison of measured velocities to theoretical predictions based on Voigt averages of elastic constants. Not only are the experimental difficulties greater in the determination of absolute velocity, but the theoretical foundation is also weaker. The Voigt procedure is generally more accurate in predicting relative variations of elastic constants than their absolute values. When Eq. (8) was applied to experimental data, the predictions of W_{400} were not physically realistic. Future efforts will be directed at other approaches, e.g., those based on the dispersion of higher order plate modes [8], to determine this coefficient.

FUTURE DIRECTIONS

It is planned that the development of this system will be completed during the next year. A number of minor technical problems uncovered by these initial tests will first be addressed. Included will be improvements in EMAT tuning to improve signal-to-noise, correction of some probe construction flaws, and use of a computer with the capacity to process more data points and thereby gain greater time precision.

Of a more fundamental nature, alternative procedures for the determination of W_{400} will be sought. From Eqs. (2)-(4), it can be seen that knowledge of the relative values of C'_{44}, C'_{55}, and C'_{66} would allow determination of W_{400} as well as W_{420} and W_{440}. Such information can be obtained from the dispersion of higher order SH modes [8], and the application of the digital system to this measurement will be investigated.

Once the full set of coefficients are determined, ultrasonic pole figures can be predicted [9]. In some cases, only one of the coefficients may be adequate for process control [6]. In either event, the speed of the ultrasonic technique with respect to x-ray or neutron measurements make it a strong candidate for practical texture control applications.

ACKNOWLEDGEMENT

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